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OBSERVATION OF STRATIFORM RAIN WITH 94 GHz AND S-BAND 1/1

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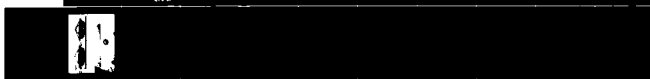
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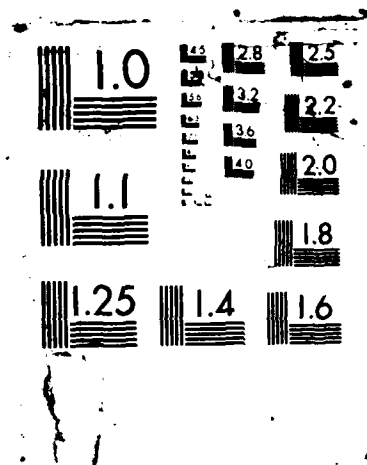
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20 September 1997

Scientific Report No. 1

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-87-0268	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Observation of Stratiform Rain With 94 GHz and S-Band Doppler Radar		5. TYPE OF REPORT & PERIOD COVERED Scientific No. 1
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dr. Roger M. Lhermitte		8. CONTRACT OR GRANT NUMBER(s) F19628-87-C0106
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Miami, RSMAS, Division of Meteorology & Physical Oceanography, 4600 Rickenbacker Causeway, Miami, FL 33149-1098		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2310G8CA
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory/LYR Hanscom Air Force Base, MA 01731-5000 Contract Manager: James Metcalf/LYR		12. REPORT DATE 9/30/87
		13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) same as 11		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) 94 GHz Doppler radar, stratiform rain, clouds		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This is a report of a pilot experiment, which took place at the AFGL site in Sudbury, MA. This experiment was concerned with the testing and operation of a 94 GHz radar to be used in a project devoted to the study of stratiform rain characteristics and evolution. Some of the data collected during the test are presented. The main experiment involving several radars operating at different wavelengths is scheduled to take place in November 1987 at the same site.		

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1. Background

The general purpose of this research is to study the physics and dynamics of stratiform rain by observing the vertical profiles of Doppler velocities and radar reflectivity using radars in a vertically pointing mode. Our specific contribution to the experimental phase of the project is to collect data with a 94 GHz (3 mm wavelength) Doppler radar, with these observations done jointly with a K_a -band (35 GHz) radar and an S-band (3 GHz) radar operated by AFGL. The research effort is divided into two phases:

a. A pilot experiment primarily concerned with a test of the installation of the 94 GHz Doppler radar at the AFGL site and its operation in all weather conditions.

b. A field experiment in the fall of 1987 with the 94 GHz radar observing stratiform rain in a vertically pointing mode in conjunction with K_a -band and S-band radar observations. The primary objectives are to observe: i. vertical profiles of radar reflectivity at the three wavelengths; ii. vertical profiles of mean Doppler (pulse pair processor) at 94 GHz and 3 GHz; iii. sampling of the full Doppler spectra at critical or sensitive altitude levels in the cloud at 94 GHz and possibly 3 GHz.

This progress report includes an account on the pilot experiment which took place during the month of May 1987 at the AFGL site in Sudbury, MA, followed by a formulation of the plans concerning our contribution to the experiment scheduled to take place at the same site in October - November, 1987.

2. Pilot experiment

The 94 GHz Doppler radar was prepared for the experiments in April 1987, left Miami on May 3, and arrived at the AFGL site on May 7. Starting on May 9, the radar was assembled and tested and its first day of operation was on May 10. The radar remained installed at the AFGL site until May 29.

Attempts to locate and buy a suitable ready-made shelter in the Boston area were unsuccessful and it was then decided to design and build a shelter using basic building supplies. After purchase of the necessary building materials, the shelter was constructed and the radar installed inside it on May 26. Fig. 1 shows a picture of the shelter and the radar. Cloud observations were done intermittently between May 10 and May 27. The

shelter was carefully dismantled and stored in a building so that it could be reassembled and used for the fall experiment. The Doppler radar was also disassembled and removed from the AFGL site on May 29.

3. Radar observations

The following Table shows a summary of the observations.

Table I

<u>Day</u>	<u>Date</u>	<u>Tape #</u>	<u>Start Time EDT</u>	<u>End Time EDT</u>	<u>Remarks</u>
Sun.	May 10	1	10:30	10:40	very thin cloud layer
Tue.	May 12	1	13:56	14:18	primarily radar testing very light precipitation
Tue.	May 12	2	14:20	15:58	bright band (not well defined)
Tue.	May 12	3	15:59	17:35	data no examined
Fri.	May 15	1	09:36	10:46	bright band data, best data
Fri.	May 15	2	15:15	16:25	no precipitation, angels
Wed.	May 20	1	15:20	15:51	overcast then blue sky, data not examined
Wed.	May 20	2	15:53	17:05	very small clouds, data not examined
Wed.	May 27	1	08:43	09:14	radar in shelter, fair weather cumulus data not examined
Wed.	May 27	3	15:40	17:29	no clouds overhead

The 94 GHz Doppler radar has the following characteristics: transmitter peak power 1.2 kw, pulse width 0.5 μ s, pulse repetition rate 10 kHz, transmitter antenna diameter 90 cm, receiver antenna diameter 90 cm. The radar is equipped with a real-time pulse-pair processor evaluating the following at 256 range gates spaced by 400 ns (60 m): the

real and imaginary terms of the pulse-to-pulse covariance, the signal complex square, and the integrated signal at the output of a logarithmic amplifier. These data are recorded on magnetic tape and then processed by a microcomputer to yield vertical profiles of the radar reflectivity, mean Doppler velocity, and spectral width.

The computation of the cloud reflectivity factor Z (or equivalent Z_e for precipitation) based on the radar characteristics is given by [Lhermitte, 1987]:

$$\text{dBZ} = P_r + 58 + 20 \log R$$

P_r is the power received by the antenna in dBm and R is the range of the target. The above equation does not include attenuation of the signal between the radar and the target, but includes an arbitrary efficiency factor of 2.5 dB for each of the antennae. The receiver noise level is -93 dBm but, with 32,000 samples contributing to the evaluation of covariance terms and mean signal intensity, echo power down to -113 dBm can be measured and the mean Doppler evaluated. Therefore a cloud at 2 km with a radar reflectivity of -49 dBZ can be observed by the radar. This estimate does not include attenuation of the signal by the clear atmosphere (approximately 2 dB/km two-way for 5 g/m³ humidity) and by clouds or precipitation. The Doppler performance of the 94 GHz radar is at least as good as that of a well-designed centimeter wave Doppler radar. Tests of the radar have shown that in very stable precipitation or cloud conditions, the standard deviations of mean velocity estimates calculated using 32,000 samples were smaller than 1 cm/s, which in this case indicated no significant contribution from Doppler radar phase noise [Lhermitte, 1987].

As mentioned above, the research performed within the AFGL contract is concerned with the study of stratiform precipitation. During the pilot experiment, such precipitation conditions only occurred on May 15 and more marginally on May 11. The May 15 data were the closest to this type of weather for which air vertical velocity is so small that "bright band" (discussed below) conditions are dominant. However, it is suspected that some convection (presence of significant up-drafts) may have occurred in the cloud at certain times. The data acquired during the pilot experiment are still being analyzed but the following is an account of the type of data collected on May 15 and some of the findings.

The data recording started at 09:36 EDT. The radar data indicated a

cloud top at approximately 8 km but there was no precipitation observed at the ground. At 09:45 very sparse drops fell but the rain was very light and not measurable. The precipitation increased steadily to reach drizzle to light rain conditions (approximately 1 mm/hour) later. The observations lasted slightly over an hour during which more than 900 vertical profiles of mean Doppler and radar reflectivity were obtained at a rate of 13 profiles per minute.

Fig. 2 shows an example of vertical profiles acquired at approximately 10:30 EDT. The maximum altitude level at which valid velocity estimates were obtained was 7 to 8 km. A -30 dBZ reflectivity, which is the radar sensitivity threshold at this altitude, was observed at that level. The reflectivity calculations include an arbitrary correction of 0.5 dB/km which is carried to the cloud top for convenience in the execution of the data processing programs. This correction which is based on 50 mg/m³ of precipitating liquid water, may be a bit too small in the liquid water below the melting level at approximately 2.7 km, and it may be too high in the ice crystal region above. However, when applied from 3 km to 7 km, this correction changes the reflectivity estimates at the cloud top by only 2 dB. Furthermore, the supercooled liquid water in the cloud may produce a comparable absorption. The maximum value for the radar reflectivity observed during that day in the rain region below 2.7 km is slightly less than 10 dBZ which agrees with the precipitation at the ground not reaching more than a millimeter an hour (with a Marshall-Palmer drop size distribution, 1 mm/hr rain produces approximately 15 dBZ at 94 GHz) (Lhermitte, 1987). The maximum value for the reflectivity observed above the melting zone (see below) was approximately 0 dBZ.

The most striking feature in the data presented in Fig. 2 (and in Fig. 3 where data are shown with an expanded scale to allow a better comparison between radar reflectivity and mean Doppler velocity profiles), is the large variation (from approximately 1.5 m/s to 4.5 m/s) of the mean Doppler in 2.9 km to 2.7 km (approximately) vertical interval. This reflects the drastic change of the fall speed of particles due to their melting, as they evolve from an ice crystal-snowflake nature to a raindrop shape. This is similar to what was observed earlier with centimeter wave Doppler radars in heavier precipitation conditions. However, centimeter wave radars also observed a well-defined maximum of radar reflectivity just

below the 0°C level (bright band) which was explained by a combination of:

1. above the maximum, an increase of radar reflectivity due to the change of index of refraction from ice to water (6-7 dB at centimeter wavelength).

2. below the maximum, a decrease of the radar reflectivity due to a decrease of the concentration of precipitation particles resulting from their acceleration through the bright band, and also to the shrinking of particle size due to melting.

These considerations are based on the assumption that each particle retains its identity with no mutual interactions, breakup, or growth when it evolves from an ice crystal-snowflake form to its final raindrop shape. However, aggregation and breakup may occur and can appreciably modify the vertical velocity and radar reflectivity profiles [Lhermitte and Atlas, 1963]. At centimeter wavelengths, all the considerations about particle radar cross section were based on the Rayleigh backscattering concept, i.e., the radar cross section always increases with particle size and is proportional to D^6 , where D is the equivalent diameter of spherical raindrops.

The vertical profiles shown in Figs. 2 through 5 exhibit the same fast particle acceleration in the melting zone, but they fail to show the reflectivity maximum. There is indeed a sharp 6-7 dB increase of radar reflectivity at the altitude where particles start to accelerate which may be attributed to the change of index of refraction between ice and water. Note that an approximately 6 dB increase of reflectivity is always observed slightly above the altitude where particles start to accelerate, regardless of the characteristics of the radar reflectivity profiles above and below (see Figs. 6 and 7, for example).

However at 94 GHz, the expected decrease of radar reflectivity below is not observed, although particle acceleration is clearly shown by the Doppler velocity profiles and must produce a decrease of particle concentration there. If we assume no significant growth or aggregation of the particles falling through the melting region, the radar cross section of these particles must increase when they are shrinking in size and accelerating during their melting. The backscattering mechanisms are obviously very complex for non-spherical particles that are not small with respect to radar wavelength (Rayleigh scattering does not apply),

especially when these particles are composed of a mixture of ice and water. However, the Mie scattering functions at 94 GHz shown in Fig. 8 indicate that the radar cross-section of a liquid sphere increases by 9 dB when it shrinks from 2 mm to 1 mm size. The local decrease of reflectivity sometimes observed above the melting region and which is sometimes associated with an increase of velocity (see Figs. 2 and 3) may be due to the same peculiarities of the Mie scattering functions.

The above remarks should be considered only as a preliminary and incomplete analysis of the May 15 data, but they bring an insight of the potential for the remote sensing of precipitation particle size and shape based on radar situations in which Mie backscattering is dominant. Mie scattering does not have to be considered for centimeter wave radars except in the case of large hailstones, but it is definitely common at 94 GHz. Therefore, by comparing the reflectivity and velocity vertical profiles with those obtained at a wavelength for which Rayleigh scattering assumption is valid (3 GHz, or even 9 GHz for instance), we may have a powerful tool for the monitoring of size and shape of precipitation particles. We could therefore trace their growth characteristics from the cloud top to the ground. However, observation of the full Doppler spectra at vertical incidence is needed to better identify and tag particle size and shape. As an example, Fig. 9 shows two spectra calculated, using a Marshall-Palmer dropsize distribution, at two frequencies 9.2 and 94 GHz. Their ratio is also shown in Fig. 10 for both ice and water spheres and is seen to be independent of the dropsize distribution and only related to particle size. The Mie oscillations are clearly visible and can be used to "tag" the particle size, independently of the usual assumption of a terminal velocity-size relationship.

The stratiform precipitation data observed on May 15 provided us with an opportunity to test the 94 GHz signal absorption characteristics of the corrugated fiberglass material which we were planning to use as a roof for the shelter. For its operation in rain (or if rain is probable) the radar was covered with a thin nylon canvas. During the test, we placed a sheet of corrugated fiberglass material on top of the canvas and then removed it. The results analyzed from the radar reflectivity profiles in both cases, indicate that there is a systematic shift of the reflectivity profiles of approximately 2-3 dB which was attributed to absorption in the fiberglass material.

4. Plans for the fall 1987 project

We are proposing to transport the 94 GHz radar to the AFGL site in an early November period to be determined by the AFGL personnel. The 94 GHz Doppler radar will be equipped with the pulse pair processor previously used but, in addition, we will have a data acquisition system capable of acquiring coherent video samples (I and Q channels) at the 10 kHz radar repetition rate, continuously at one to possibly three range gate(s). The gate(s) will be selected or scanned to follow a sampling scheme designed for acquisition of the Doppler spectra at sensitive altitude levels in the cloud, primarily in the melting zone. The radar pulse width can be selected to be either 100, 200, or 400 ns. A 200 ns pulse width offers a 30 m vertical resolution and will require 16 (one-gate) or 8 (two-gates) steps to cover 600 m. The data shown above indicate a 200 m melting zone thickness so that the 600 m scanning interval will be adequate to investigate the melting band even for heavier precipitation for which the melting band thickness is expected to be greater. To provide clear perception of the spectrum shape, we are planning to record 8192 (8-bit) I and Q samples (0.8 s signal dwell time) for the evaluation of each spectrum. The Nyquist Doppler velocity domain at the 10 kHz PRF is ± 8 m/s; if the spectrum needs to be resolved in 256 points (3 cm/s between spectral lines) 64 degrees of freedom will be available for each spectral density estimate. The data will be recorded on magnetic tape or possibly acquired by a data acquisition board inserted in an AT computer with the data directly transferred to the computer hard disk at a 60 k sample (12-bit) maximum rate. With the 30 Mbyte disk capacity and one gate, 16 minutes of data can be recorded. The spectra will be computed off-line using a microcomputer equipped with FFT hardware and software. All of this equipment was budgeted on another contract and there is no request for additional funds to support this improvement of the 94 GHz radar system.

References

- Lhermitte, R.M., 1987. A 94 GHz Doppler radar for cloud observations. J. Atmos. Ocean Tech., 4(1), 36-48.
- Lhermitte, R.M., and D. Atlas, 1963. Doppler fall speed and particle growth in stratiform precipitation. Proc. Tenth Wea. Radar Conf., Boston, Am. Meteor. Soc., 297-302.

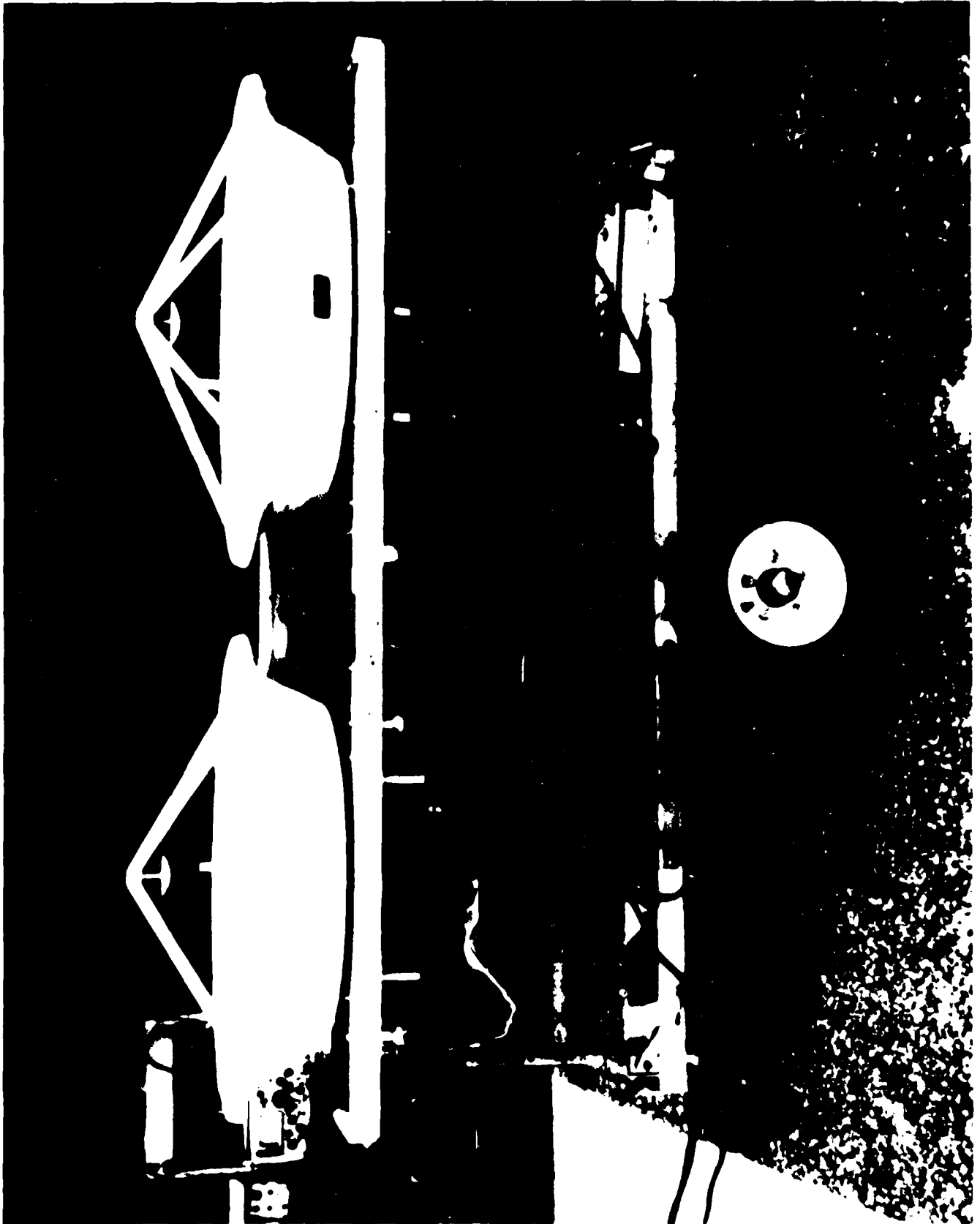


Figure 1: Photograph of Radar May 15, 1987

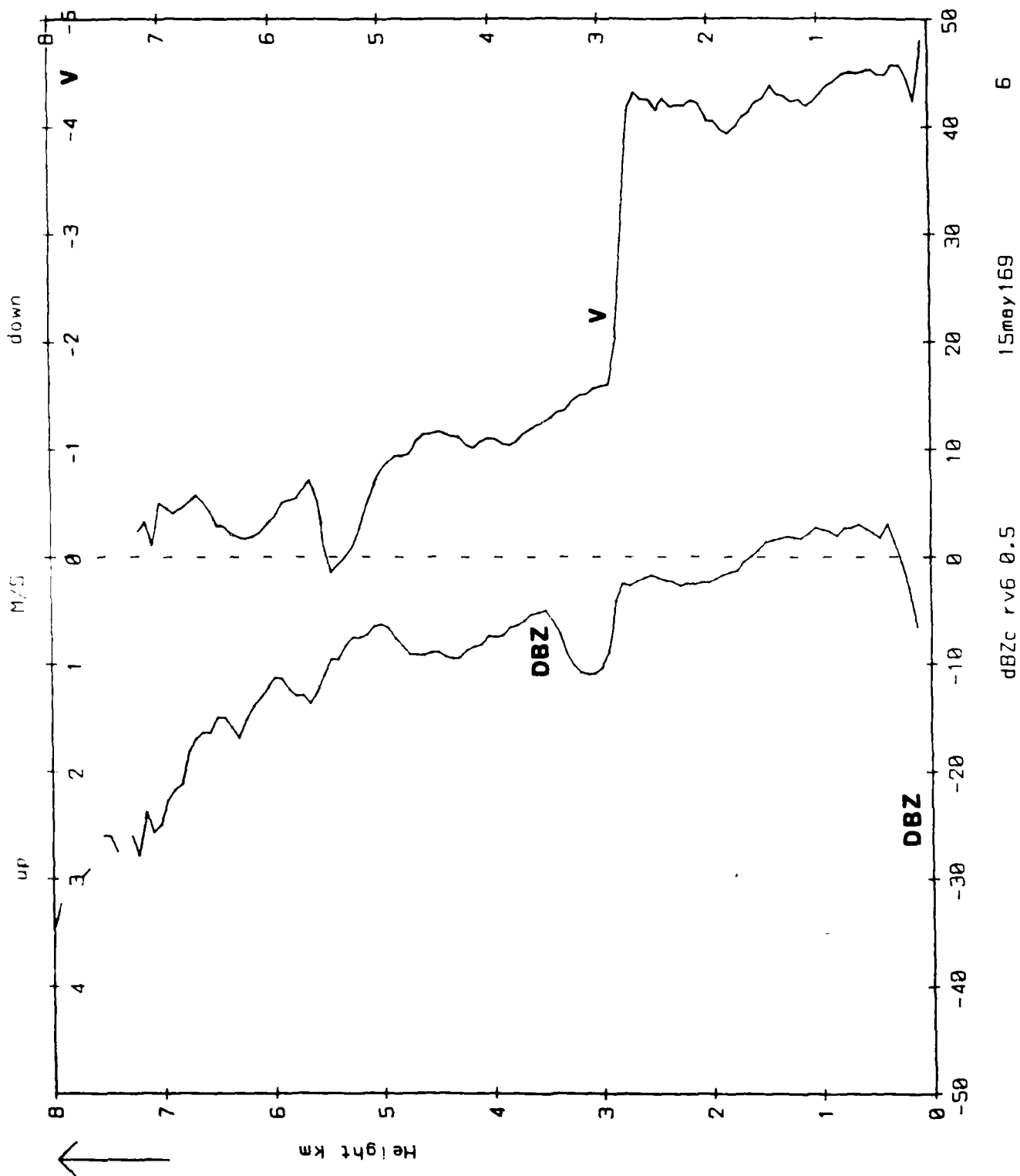
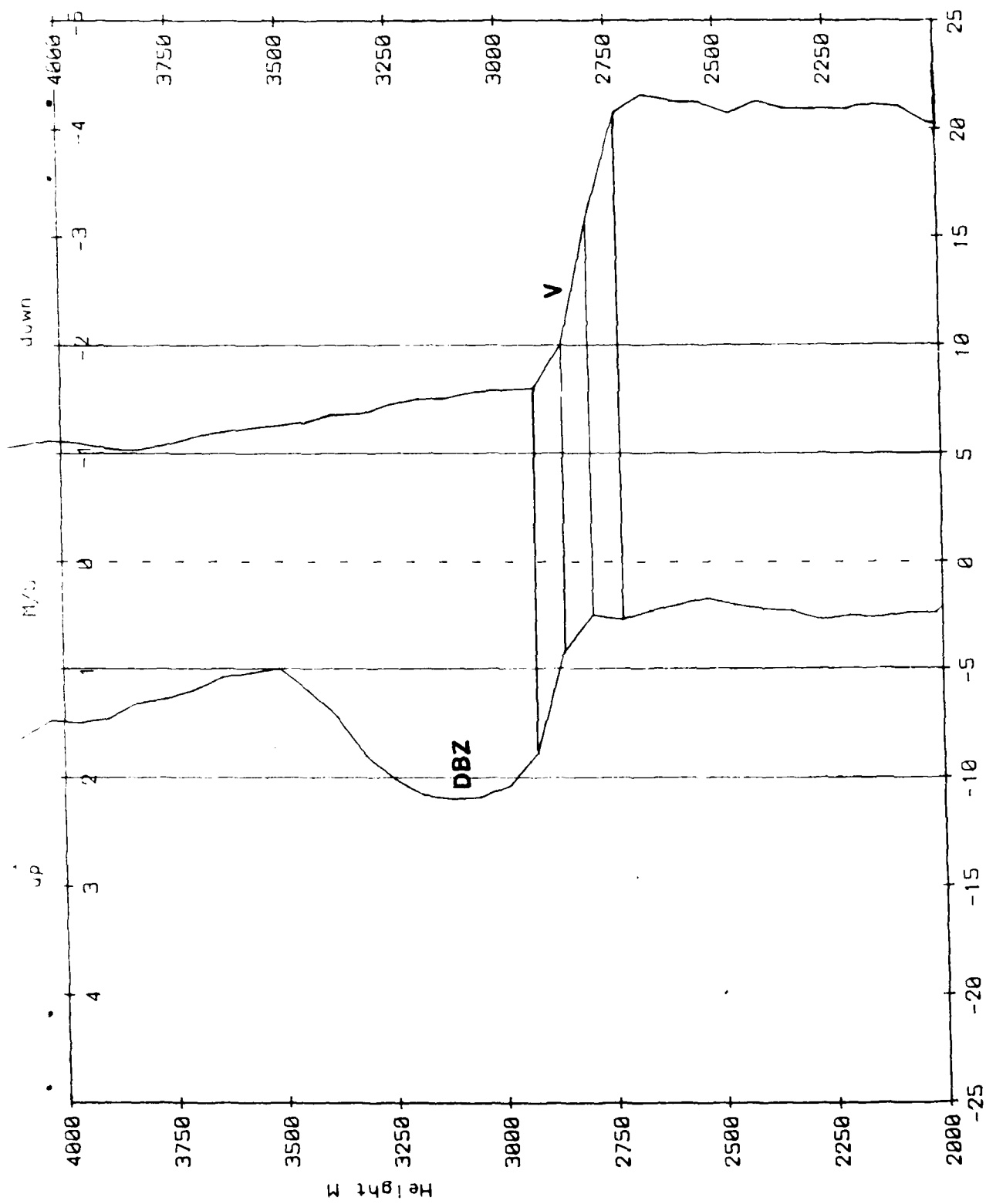


Fig. 2. Vertical profiles of radar reflectivity and mean Doppler at approximately 10:30 EDT.



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Fig. 3. Same as Fig. 2 but data are plotted with an expanded vertical scale to show the detail of radar reflectivity and mean vertical Doppler in the melting zone.

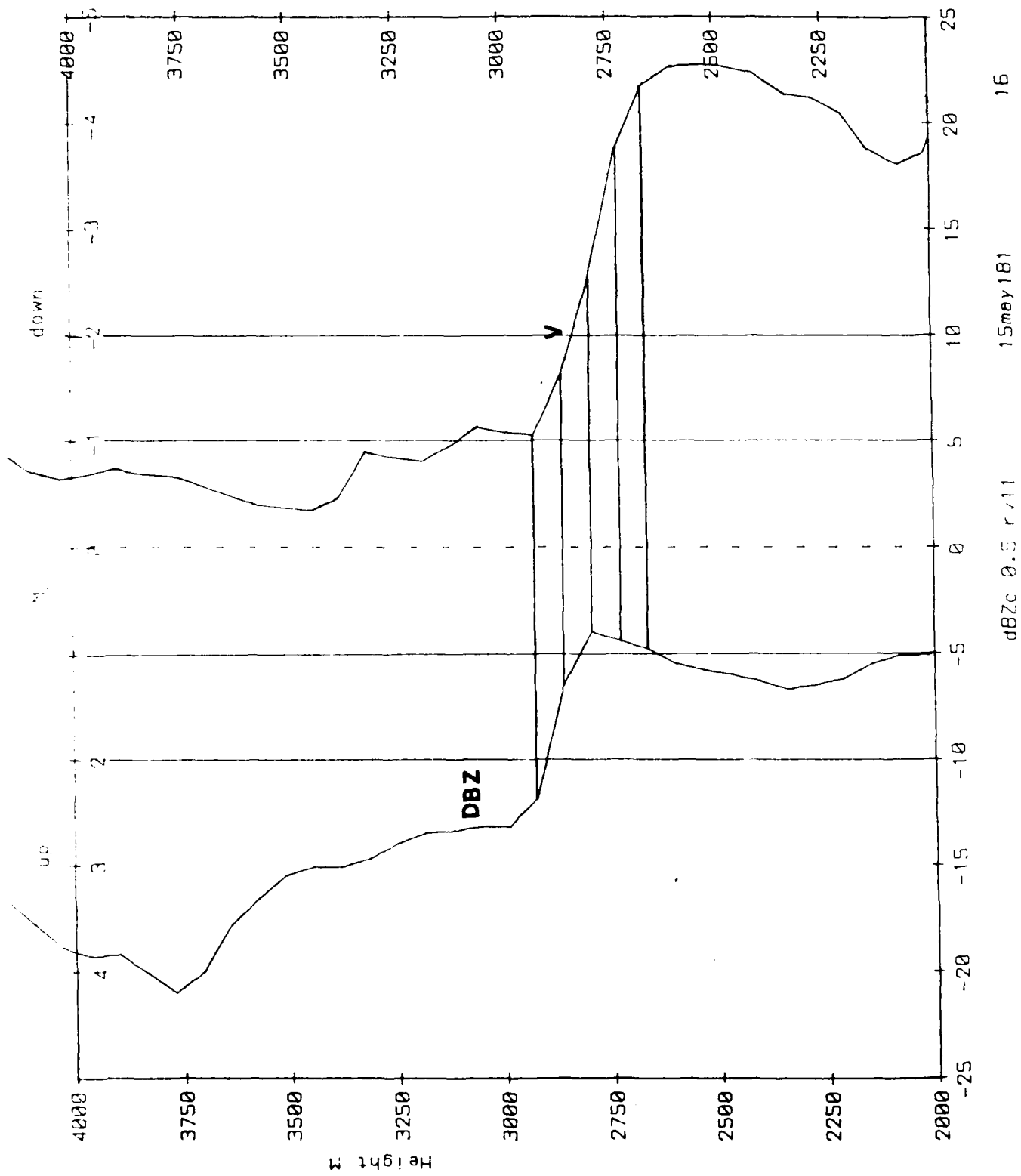


FIG. 4. Same as FIG. 2 but for data observed at approximately 10:30 EDT.

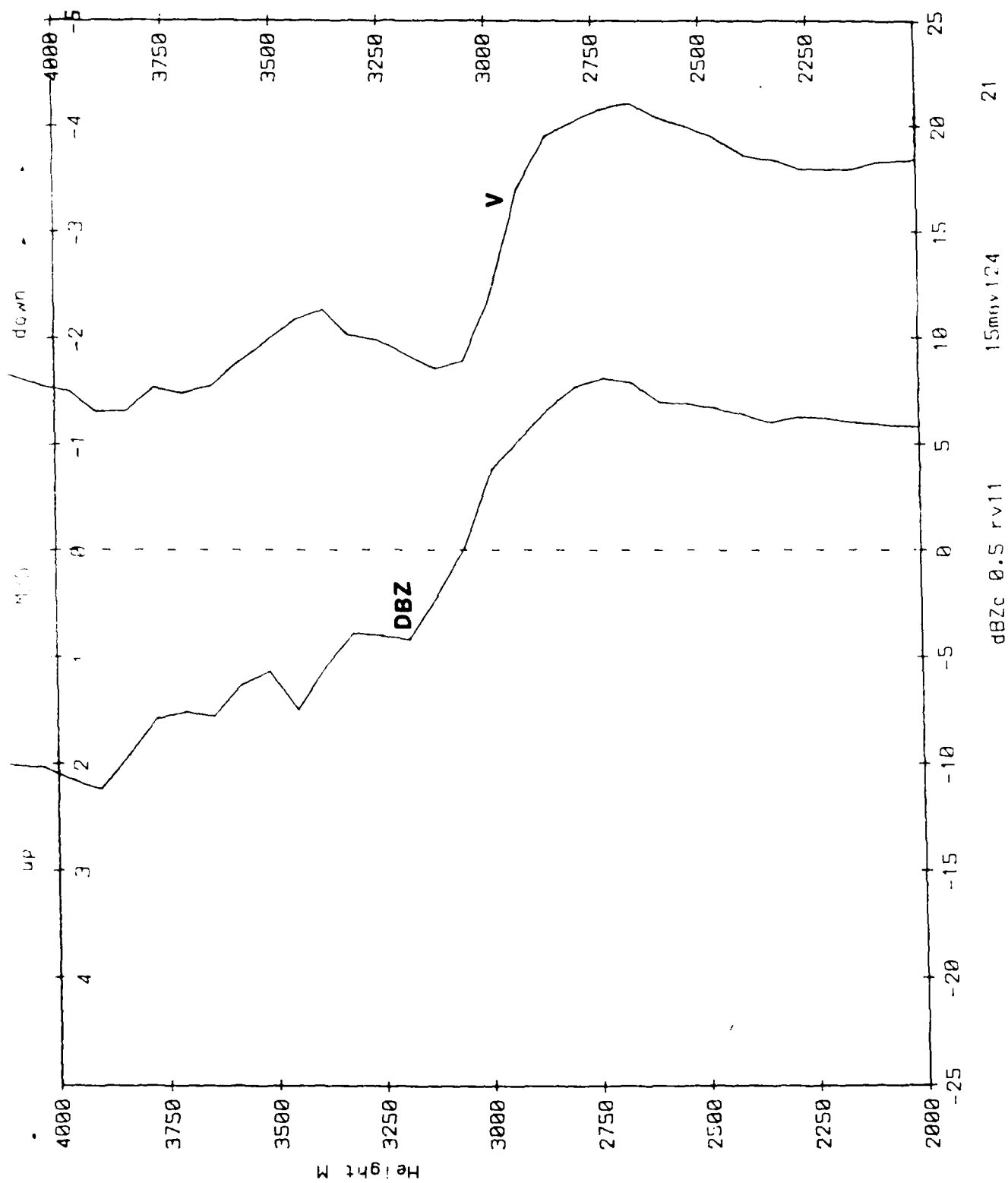


Fig. 5. Same as Fig. 2 but for data observed at approximately 9:56.

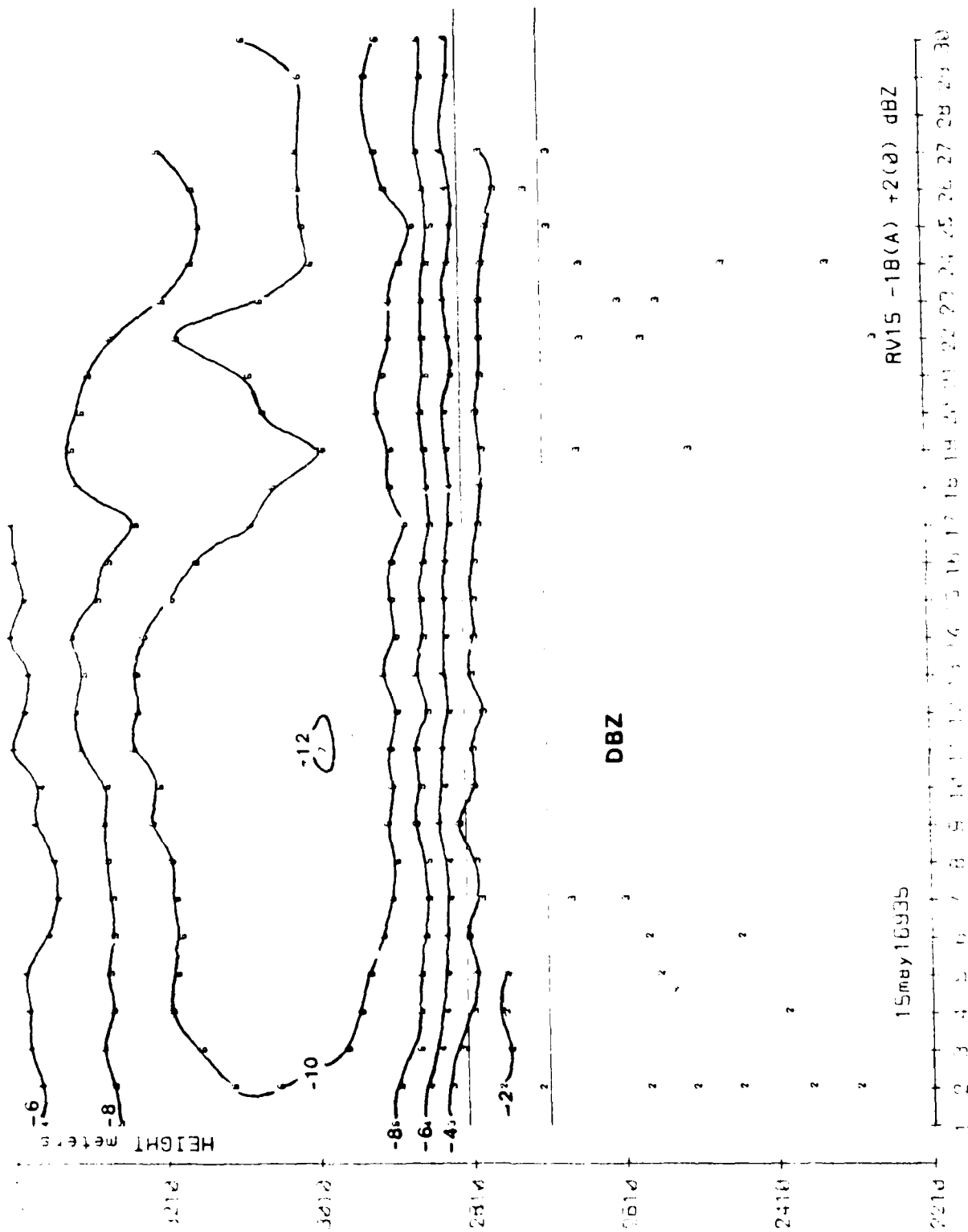


Fig. 6. Time-height display of radar reflectivity contours in the vicinity of the melting zone. Time starts at 10:28:00 and ends at 10:30:30, approximately.

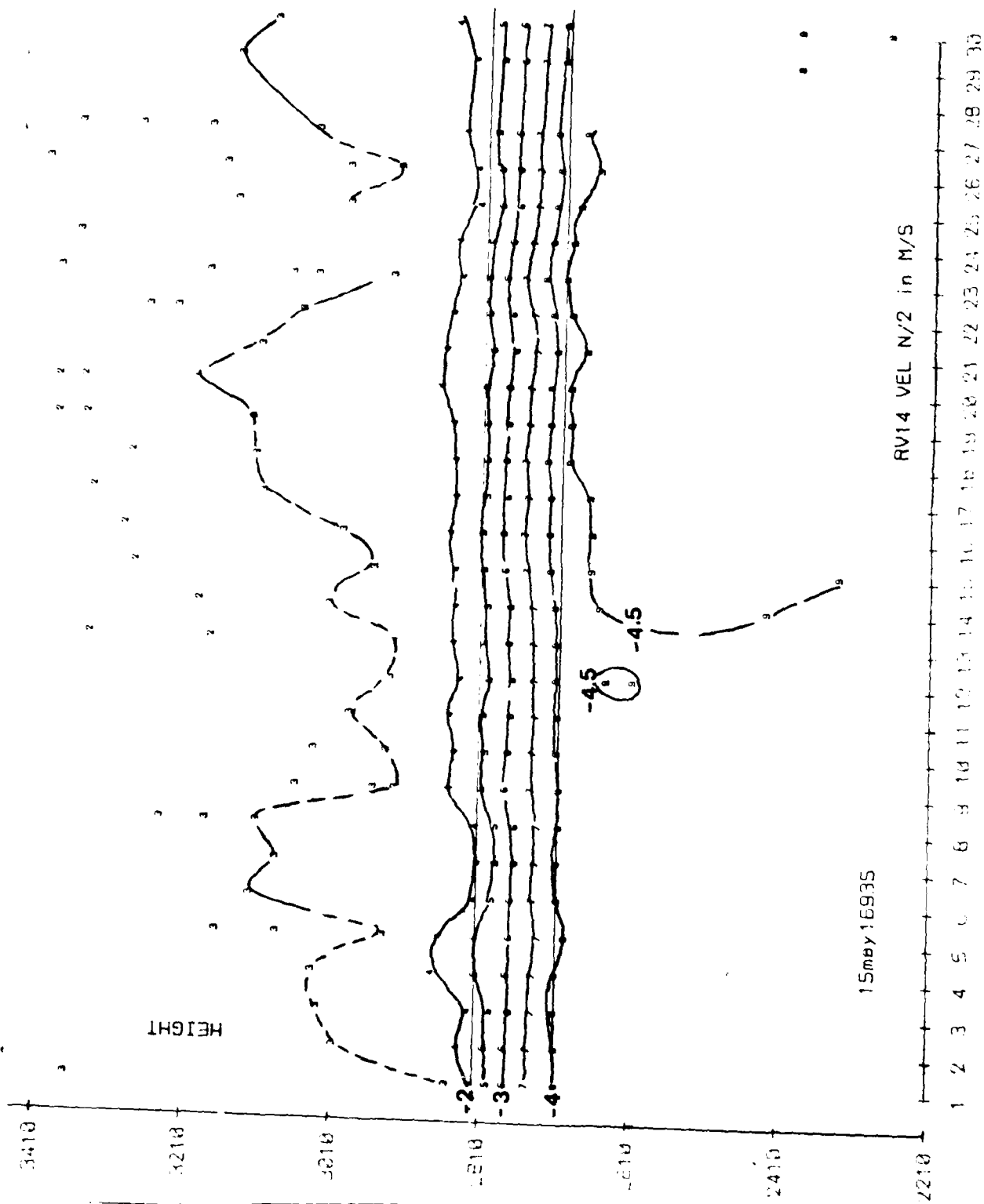


Fig. 7. Same as Fig. 5 but for the mean vertical velocity contours in m/s .

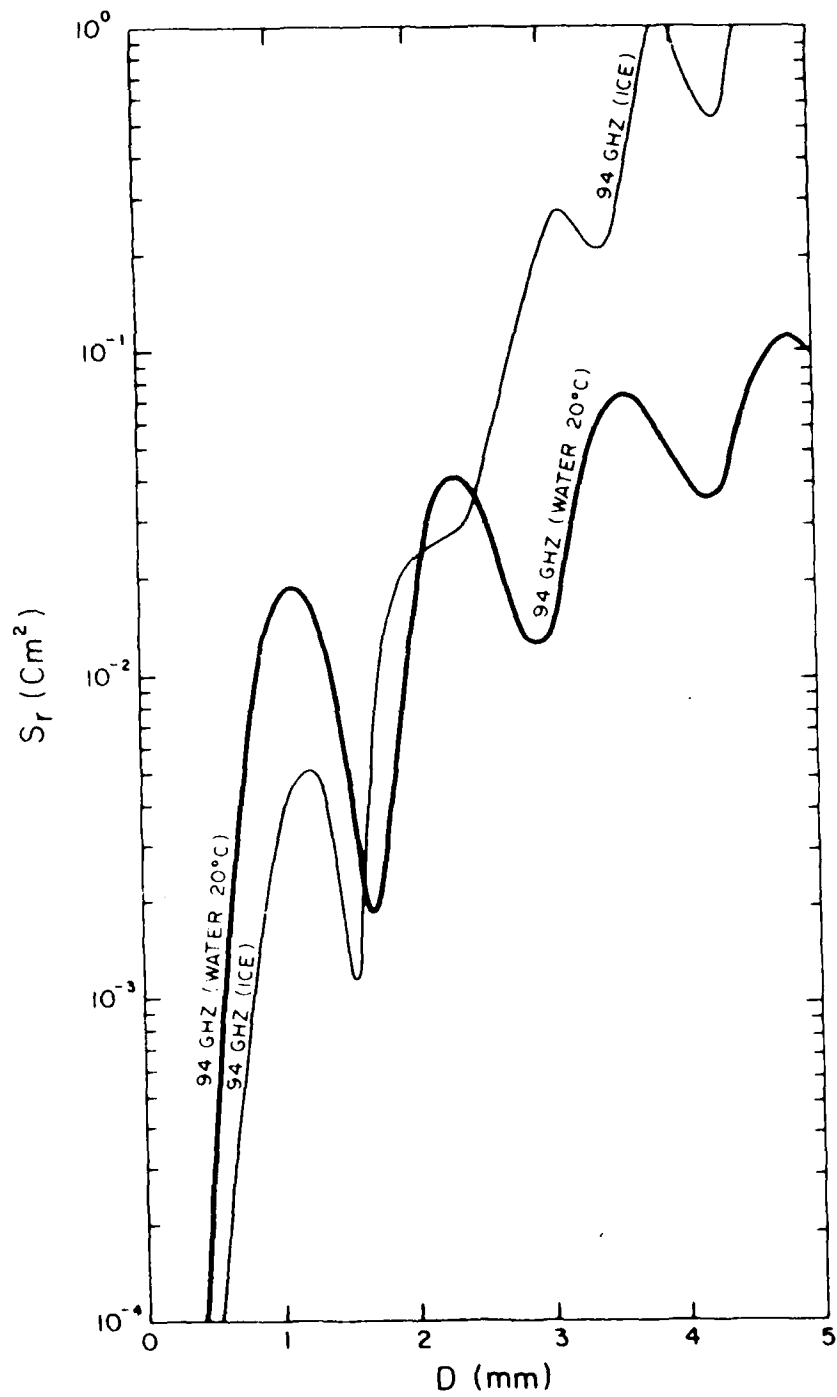


Fig. 8. Backscattering cross section of water and ice spheres at 94 GHz.

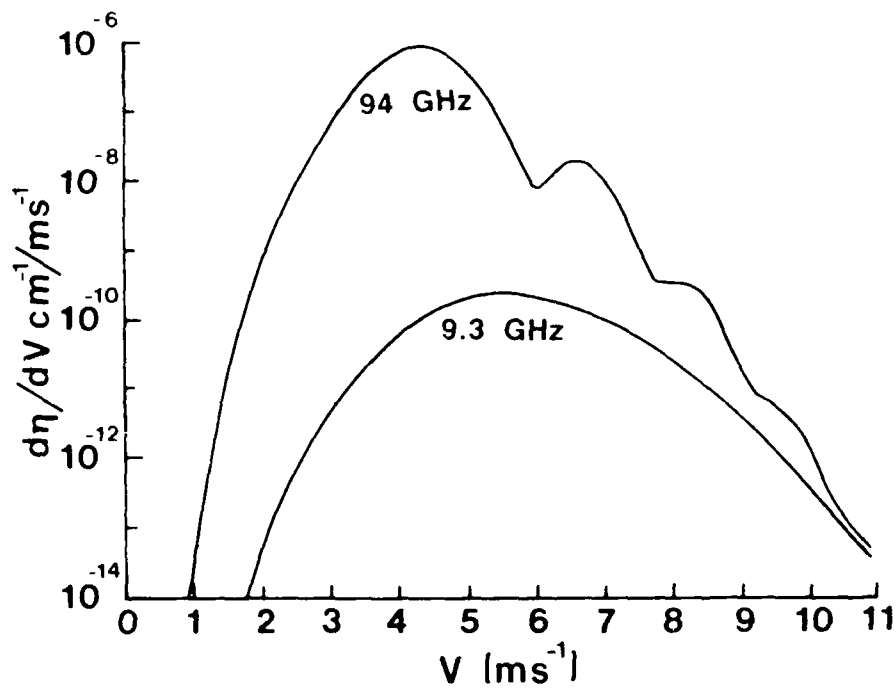


Fig. 9. Doppler spectrum at vertical incidence for a 1 mm/hr rainfall assuming a Marshall-Palmer dropsizes distribution, calculated at 94 GHz and 9.3 GHz radar frequency.

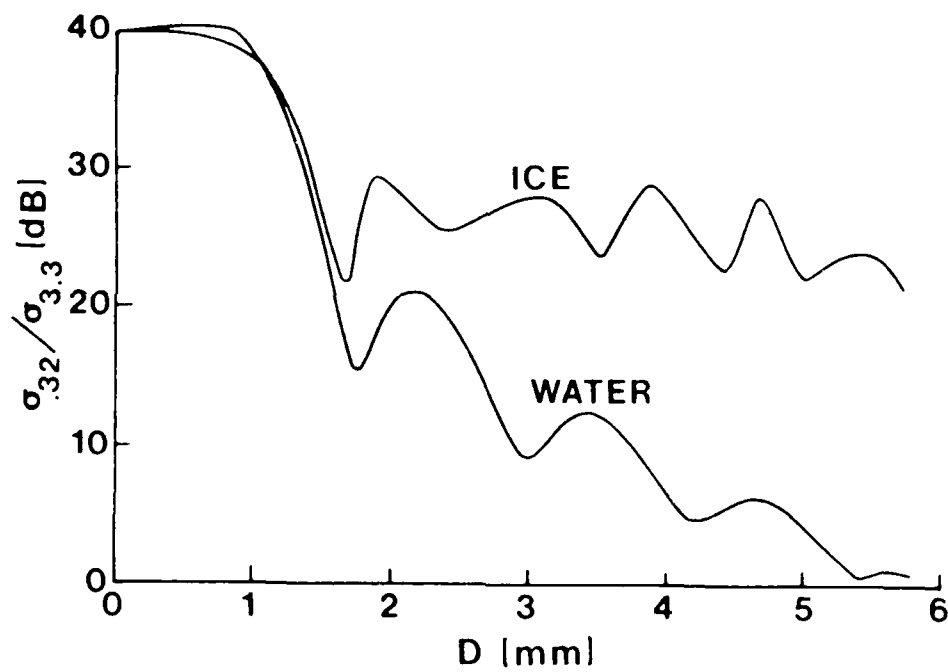


Fig. 10. Ratio between Doppler spectra at .32 cm and 3.3 cm wavelength as a function of particle diameter. The results are also shown for ice spheres.

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